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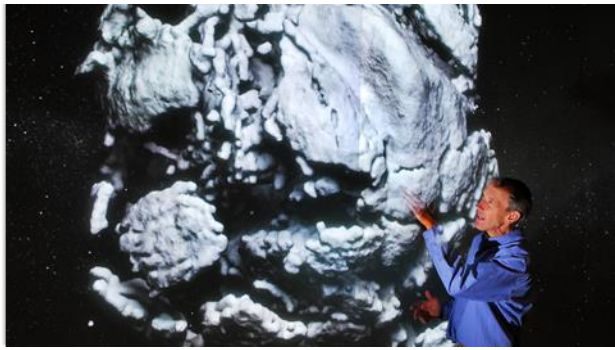

Specifications for Advanced PV Inverters:

Functions, Settings, and Communications

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Photovoltaics and Distributed Systems Integration Department

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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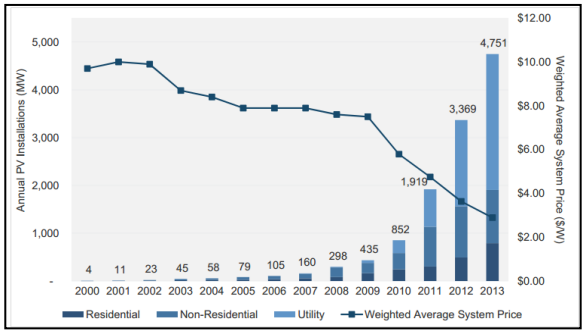
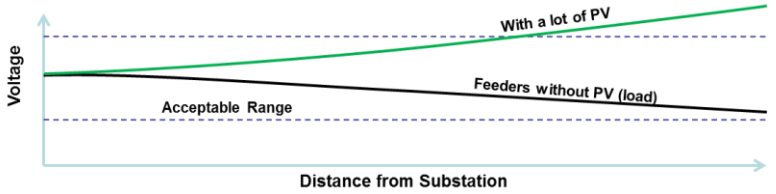
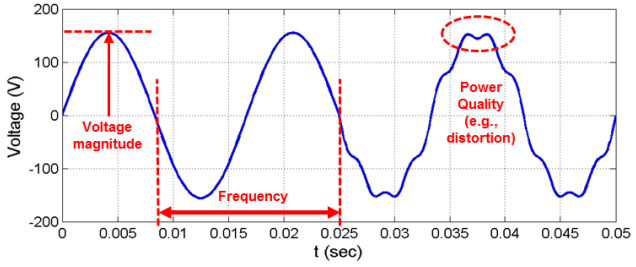
Outline

- The context
  - Total installed capacity of PV is growing fast
    - Aiming for 12 GW of grid-connected renewable energy in CA by 2020!
  - Large growth expected in distribution systems
- New problems
  - Voltage & frequency control
  - Protection and disturbance recovery
  - System stability
- Advanced inverters are a big part of the solution, but we need:
  - Definitions for advanced grid **functions**
  - Recommendations for default **settings** for advanced functions
  - Reliable and secure **communication** methods for interoperability



Source: GTM Research, US Solar Market Insight 2013 Year in Review





Current Electricity Grid

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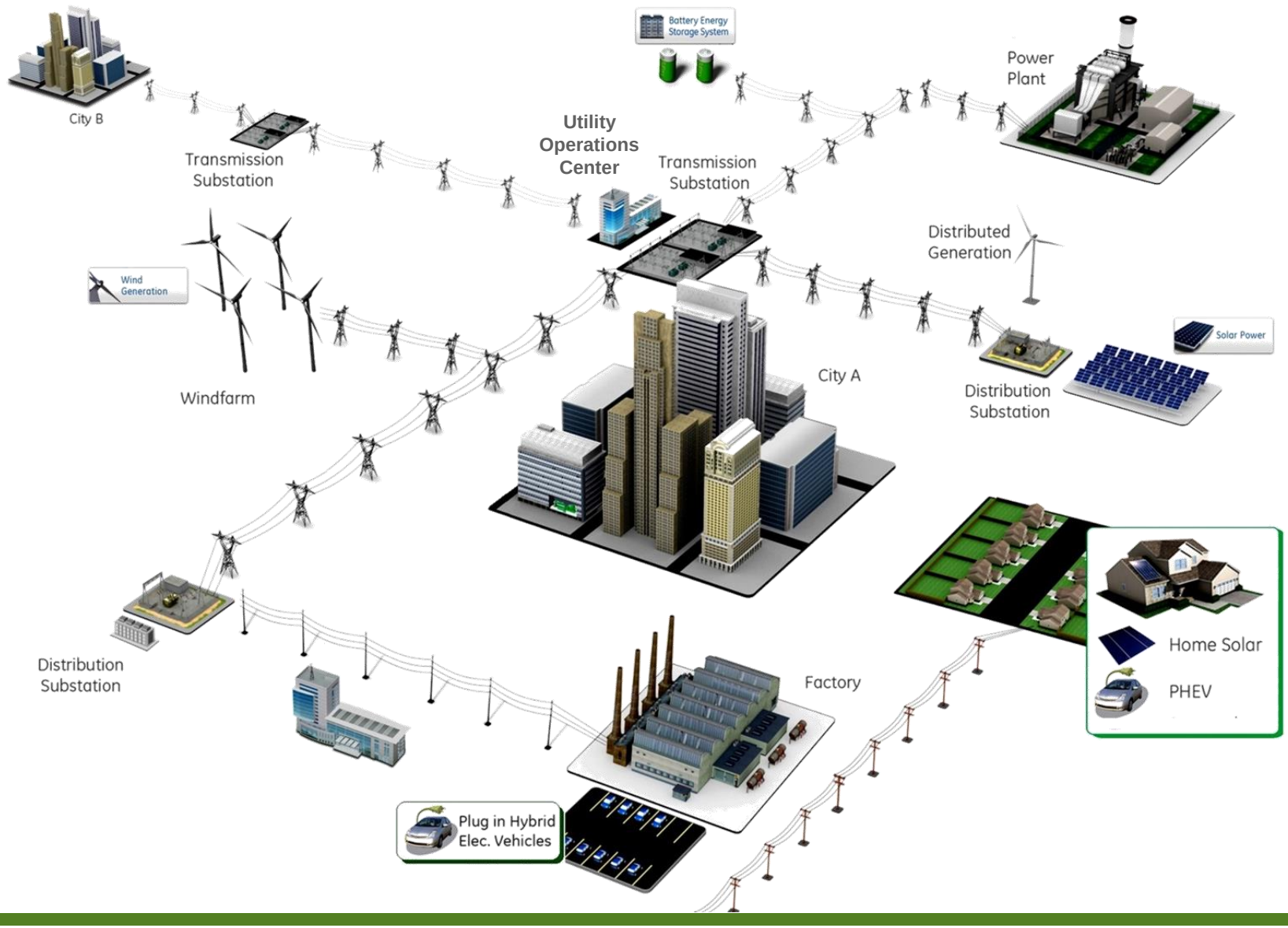

Image: Forbes India

Current Electricity Grid Communications

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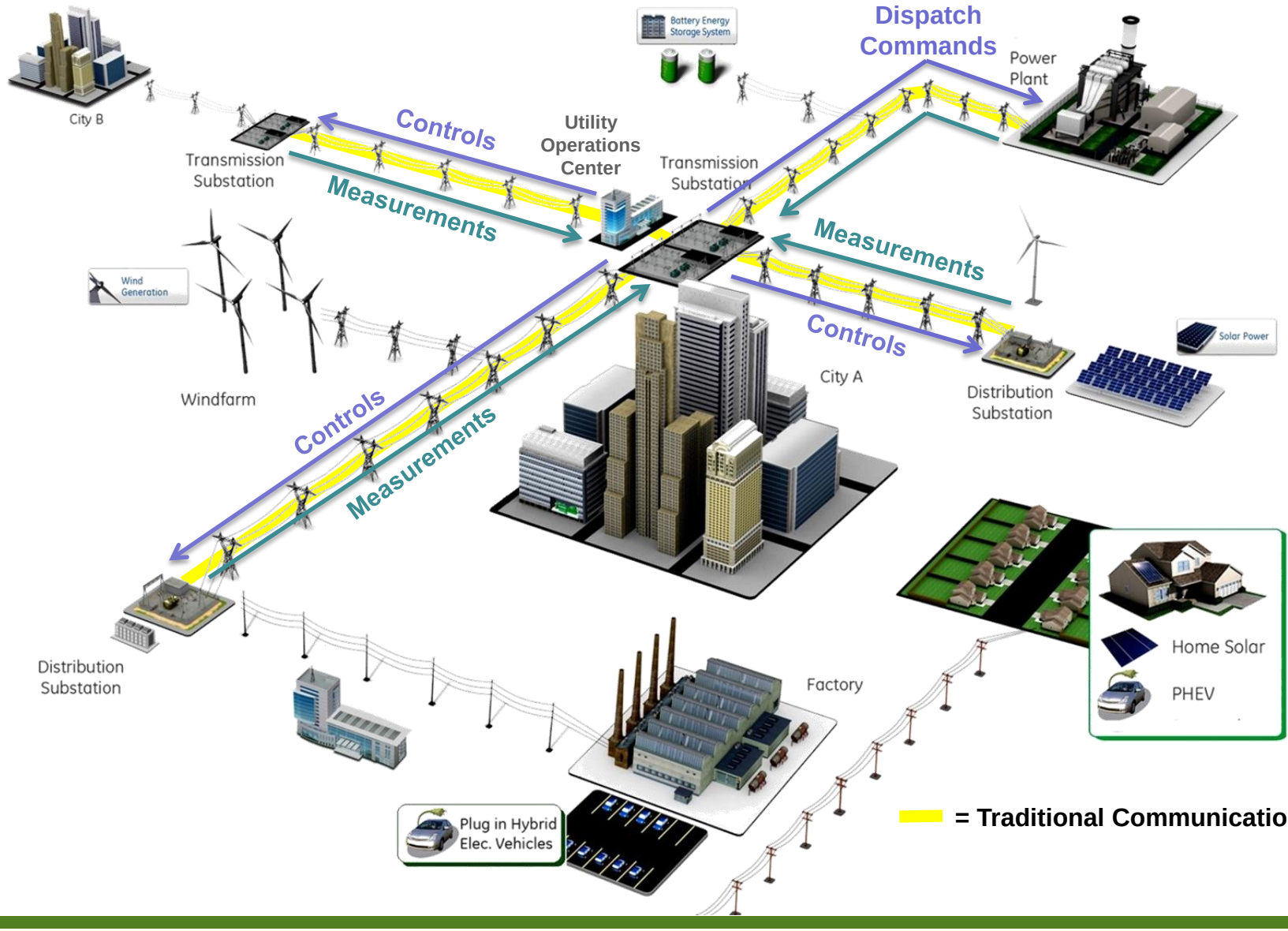

Image: Forbes India

Smart Electricity Grid Communications

Sandia National Laboratories

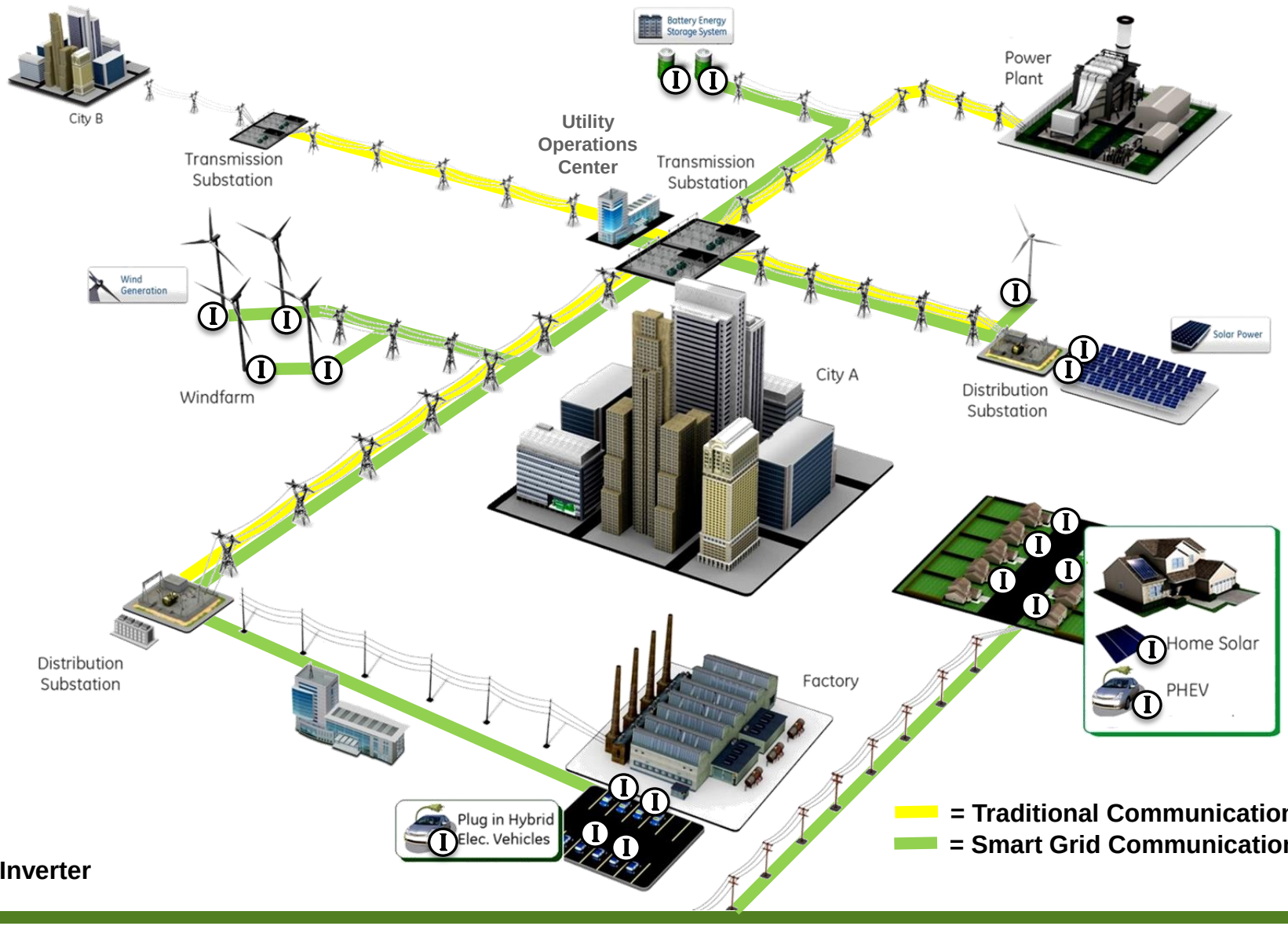

Image: Forbes India

Smart Electricity Grid Communications

Sandia National Laboratories

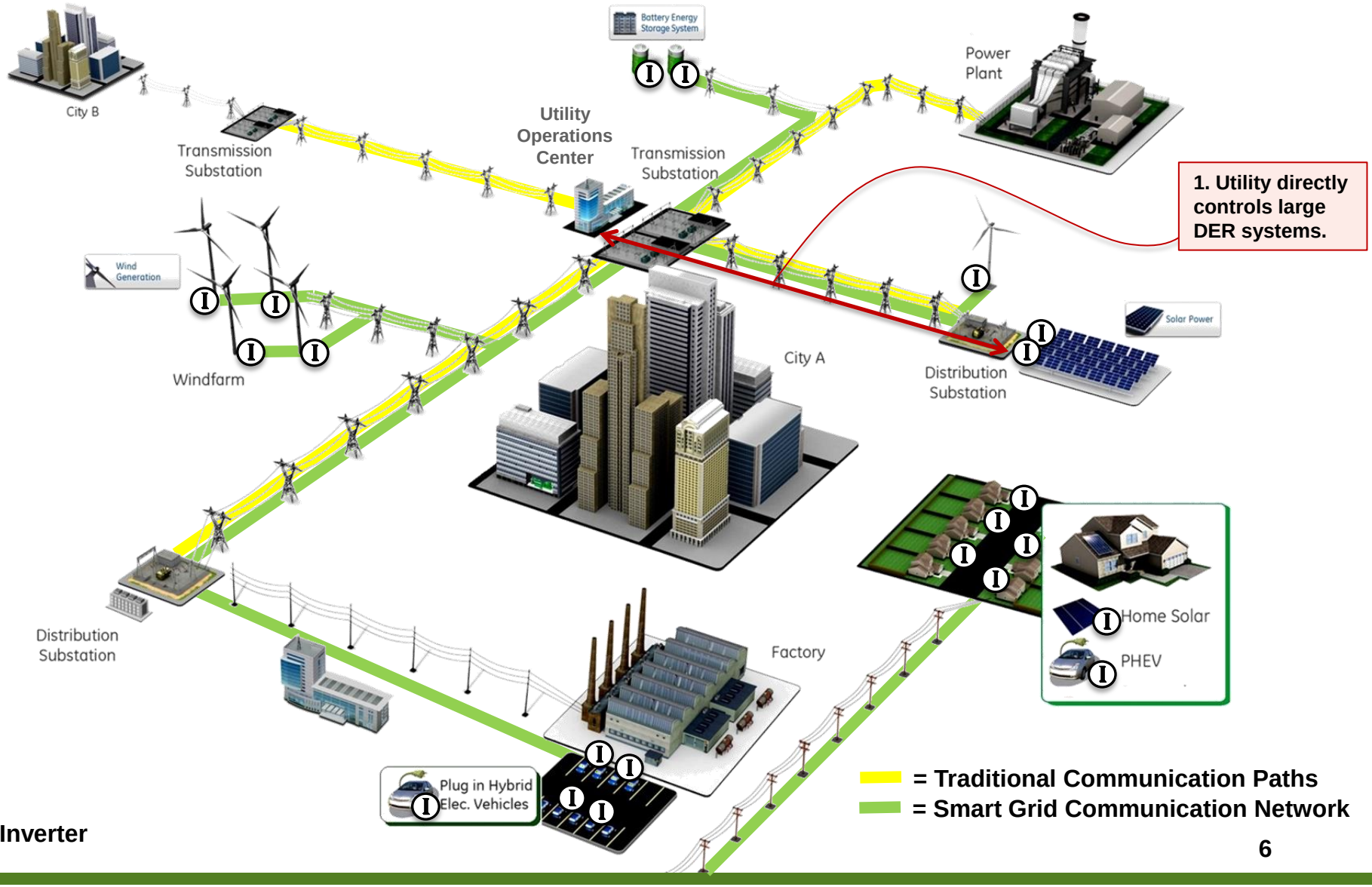

Image: Forbes India

Smart Electricity Grid Communications

Sandia National Laboratories

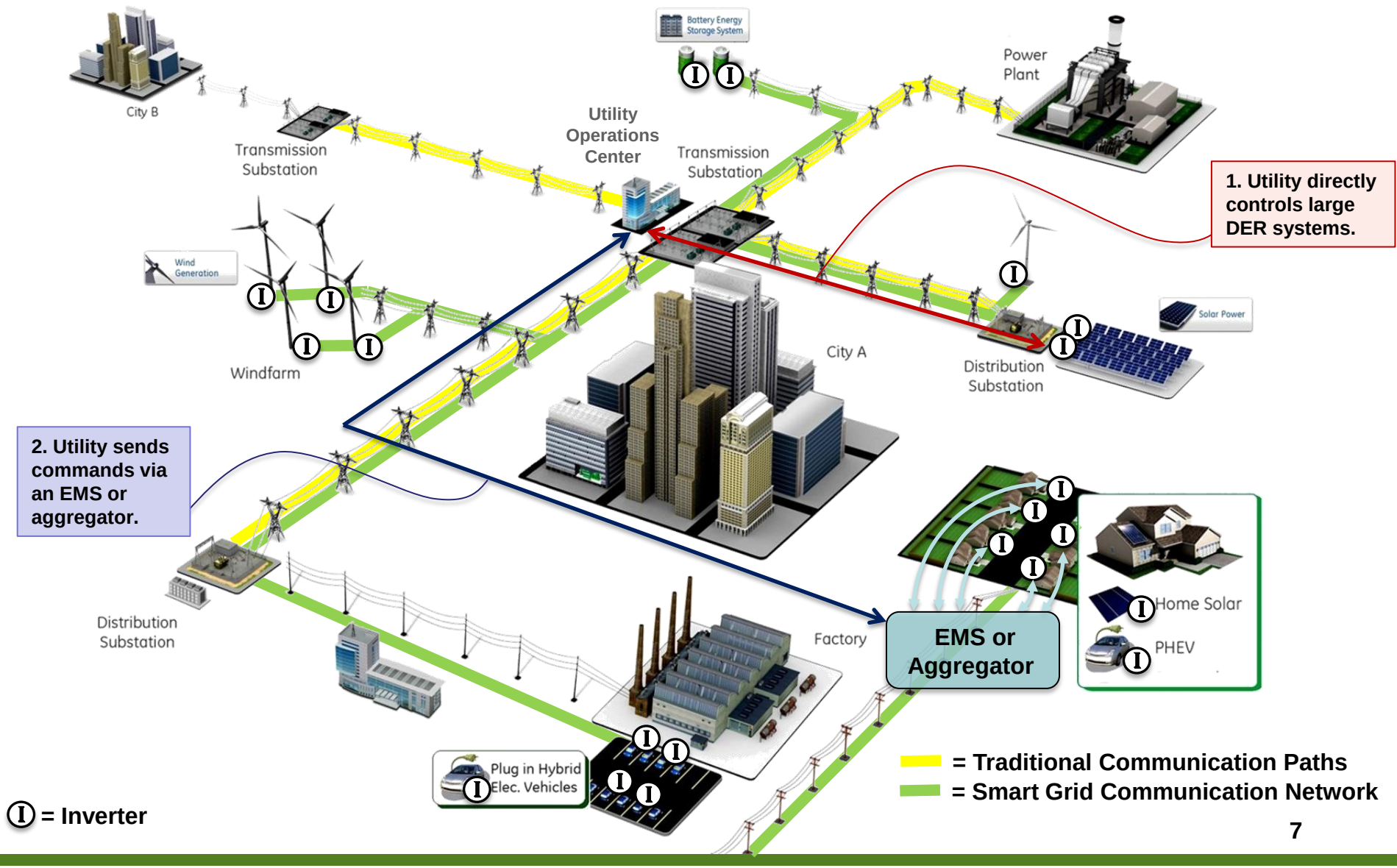

Image: Forbes India

Smart Electricity Grid Communications

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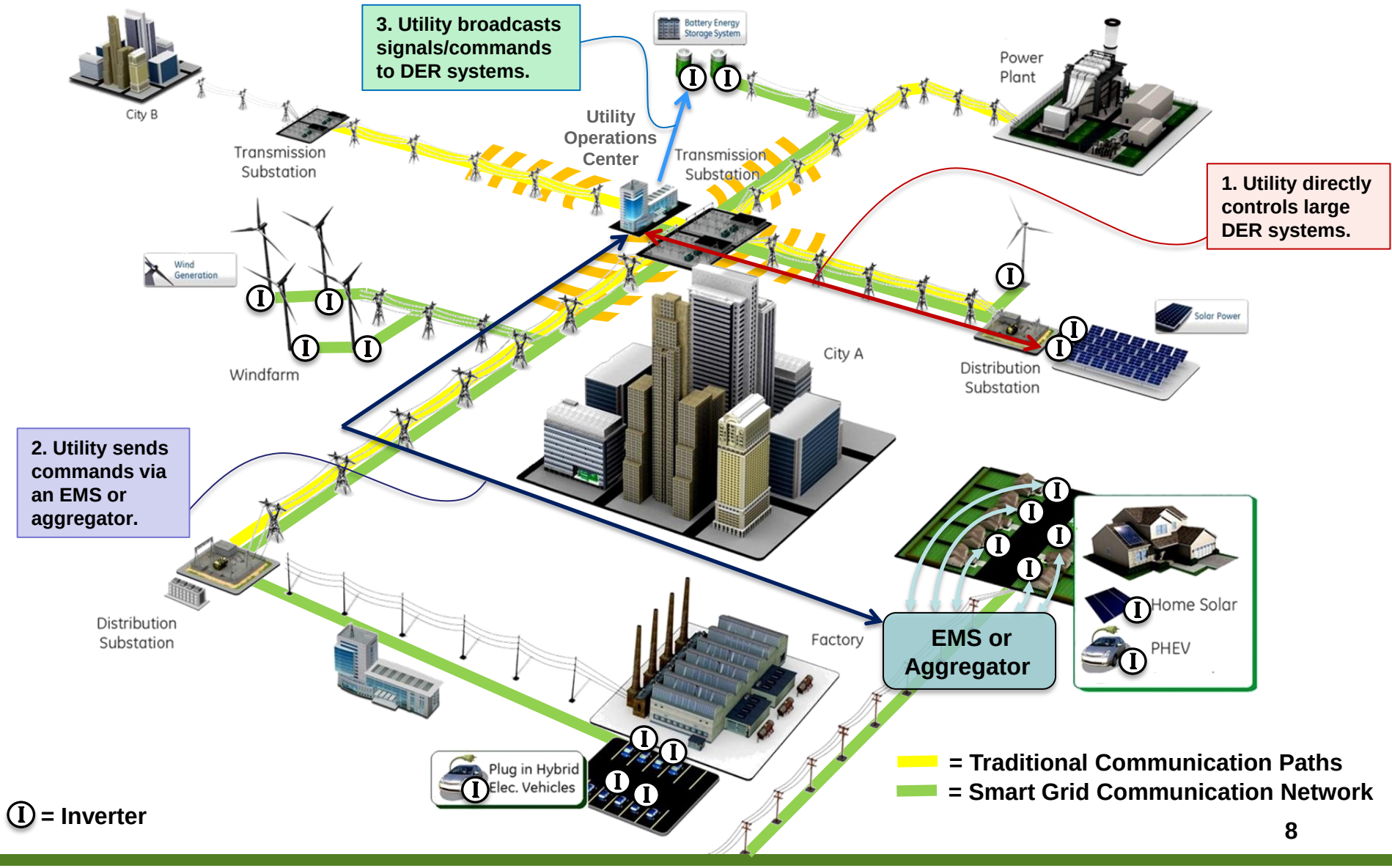

Source: Forbes India

Types of Advanced Inverter Functions

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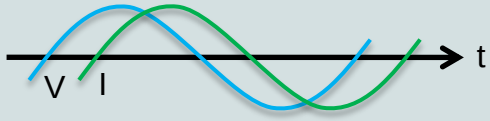
Advanced functions defined in IEC Technical Report 61850-90-7:

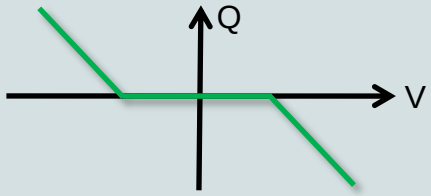
NOTE: CA Rule 21 SIWG defined similar functions.

Voltage Support

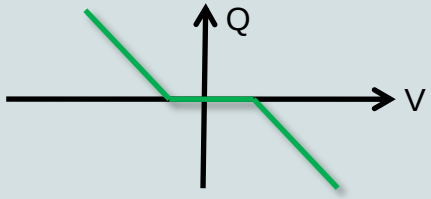
- **Adjust Power Factor (INV3)**



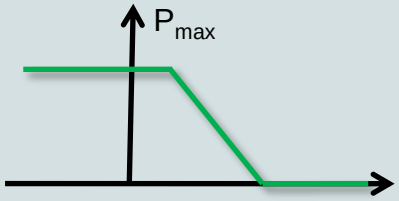
- **Volt-Var Mode (VV11, VV12, VV13)**



- **Dynamic Reactive Power (TV31)**



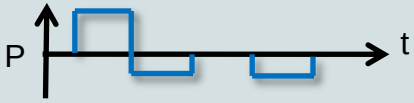
- **Volt-Watt Mode (VW51; VW52)**



Frequency Support

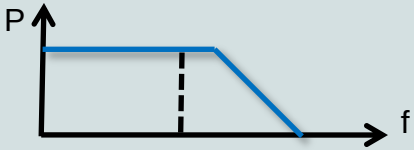
- **Adjust Maximum Active Power (INV2)**

- **Request Active Power from Storage (INV4)**

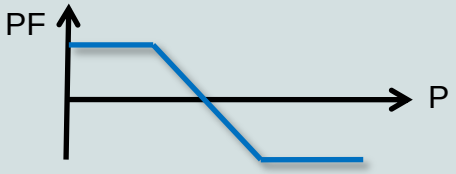


- **Signal for Charge/Discharge (INV5)**

- **Frequency-Watt Mode (FW21, FW22)**

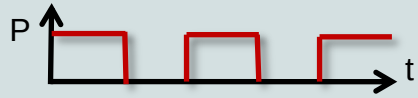


- **Watt-Power Factor (WP41, WP42)**

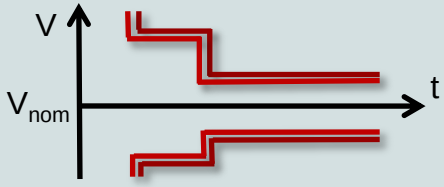


Grid Protection (Response to Disturbances)

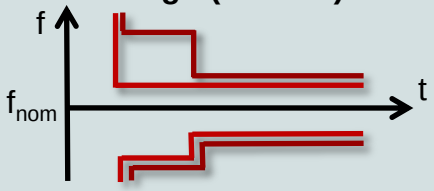
- **Connect/Disconnect (INV1)**



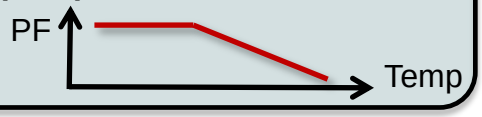
- **Low and High Voltage Ride Through (L/HVRT)**



- **Low and High Frequency Ride Through (L/HFRT)***



- **Temperature Mode Behavior (TMP)**



*FRT not included in IEC 61850-90-7, but is included in Rule 21 SIWG recommendations and Sandia Test Protocols.

Sandia Advanced Inverter Test Protocols

- General guidelines for harmonized equipment testing across different laboratories.
- Precursor to equipment certification procedures.
  - No pass/fail criteria
  - Only suggestions for advanced function parameter sets
- Two distinct phases for most functions:
  - Communication
    - Send the signal from the Utility Management System (UMS) Simulator
    - Verify the communications reached the EUT
  - Electrical behavior characterization
    - Measurement of the DC and AC characteristics to verify the inverter updated its operation

Example Function: INV1 (Connect/Disconnect)

- Advanced functions include multiple settings in additional to the curves/activation
  - e.g., time window, timeout period, and ramp rate

INV1 Test Protocol Sequence.

	Step	Task	Function	Notes
Communication	1	Request Status to EUT.	**DS93** (Status Reporting) & Direct of inverter output	Log time sent.
	2	UMS receives response to DS93.command.		
	3	Inverter output is measured and logged		sensors record inverter output
	4	UMS issues a Disconnect /Connect Command to EUT.	**INV1** – Connect/ Disconnect	Log time sent. Command may include the following parameters: timeout period (optional) ramp rate (optional)
	4	EUT responds to the command	**DS92** – change in	Expected response message from EUT: and DM monitored output) Rejected (includes reason)
Electrical Behavior	5	Verify command was successfully executed (DS92 and	**DM** – EUT output is recorded & logged	Monitor electrical output of EUT to determine if EUT connects/ Measure voltage, current, power factor Record time
	6	Repeat test with varying parameters (see Table A1-3). Each test at least once as needed.	–	
Analysis	7	Characterize EUT's response.	**DS92; DM**	Determine how command was executed.

Utility Requests Inverter Status

Utility Receives Inverter Status

Utility Logs Inverter Status

Utility Issues INV 1 Command to Inverter

Inverter Changes Operation and Confirms

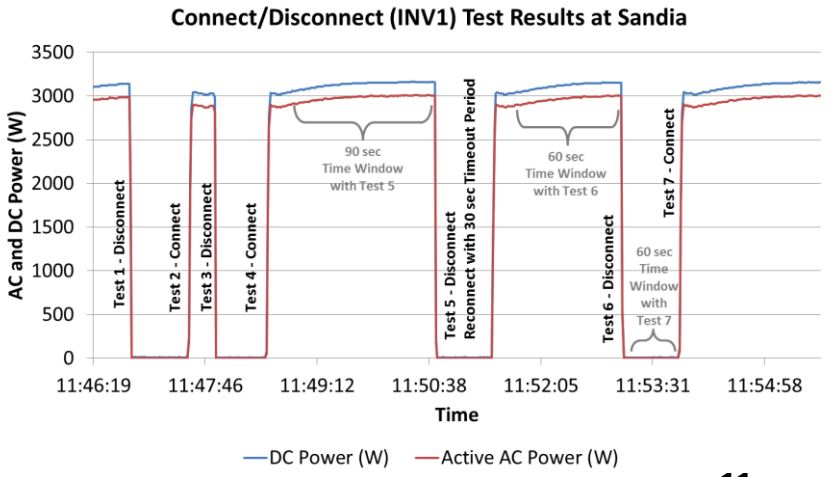
Electrical Output is Monitored, Verify Operation

Repeat INV1 Tests with Range of Parameters

Analyze Electrical Behavior (Assign Pass/Fail)

INV1 Test Matrix.

Test Number	EUT Initial Operating State	Connect/Disconnect Command	Time Window (seconds)	Timeout Period (seconds)
Test 1	>50% rated power, unity power factor	Disconnect 1	Default (e.g., 0)	Default (e.g., 0)
Test 2	Inverter off	Connect 1	Default (e.g., 0)	Default (e.g., 0)
Test 3	>50% rated power, unity power factor	Disconnect 2	0	Default (e.g., 0)
Test 4	Inverter off	Connect 2	0	Default (e.g., 0)
Test 5	>50% rated power, unity power factor	Disconnect 3	90 seconds	30
Test 6	>50% rated power, unity power factor	Disconnect 4	60 seconds	0 (No Timeout)
Test 7	Inverter off	Connect 4	60 seconds	0 (No Timeout)



Advanced Inverter Communications

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- Data transfer from the utility/aggregator to the DER is a major challenge!
  - Interoperability
  - Cybersecurity
  - Communication latency, network dropouts, etc.
  - Competing communications solutions
    - Protocol: DNP3, SEP, IEC 61850, Modbus, OpenADR, SunSpec
    - Medium: Wi-Fi, PLC, Ethernet, Zigbee, Bluetooth
    - Method: Direct, Broadcast

- Sandia has partnered with EPRI, SMA, Fronius, SCE, SMUD, and SunSpec to develop communications specifications for interchange over Modbus, SEP, and Zigbee gateways. Sandia will:
  - Create test protocols for the certification/conformance of CA Rule 21 inverter functions and interoperability requirements.
  - Address cybersecurity concerns by establishing the underlying rules for the utility-to-DER communications.

CA Electric Rule 21
Phase 1 Autonomous Functions

	Function
1	Anti-Islanding Protection
2	Low/High Voltage Ride-Through
3	Low/High Frequency Ride-Through
4	Dynamic Volt/Var Operations
5	Ramp Rates (Normal, Emergency, Soft Disconnect)
6	Fixed Power Factor
7	Reconnect by “Soft Start” (Ramp and/or Random Start)

SunSpec-Sandia Collaboration

- SunSpec has defined Modbus map specifications for DER devices so 3rd parties can adjust functions/settings

- Sandia and the SunSpec Alliance are collaborating to establish tools for verifying IEC 61850-90-7 functions:
  - Works for all SunSpec-Compliant PV Inverters (and other devices)
  - Modes of operation: direct manipulation of Modbus registers, python scripting, and interaction via a graphical user interface.

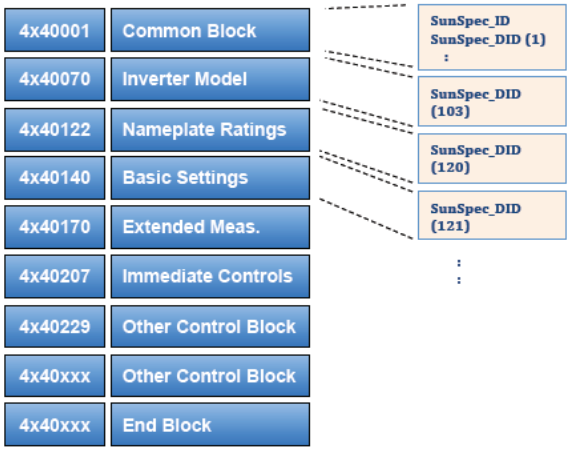
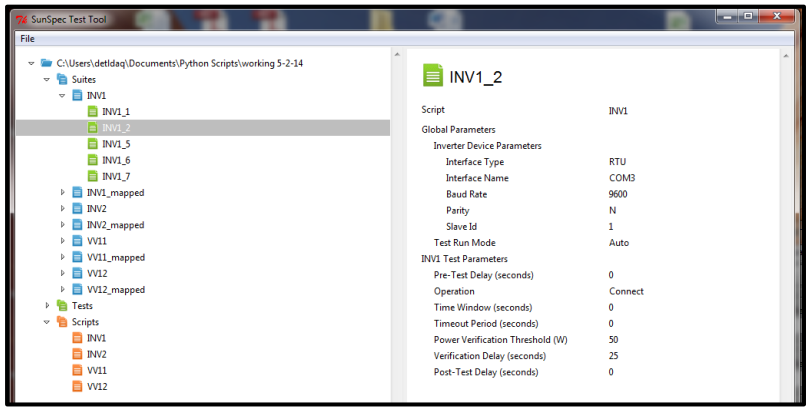


Figure 1: Chained Inverter Control Blocks



GUI Version of the SunSpec Test Tool

Video of SunSpec Test Tool at Sandia

- Demo of the SunSpec Test Tool communicating with and verifying the operation of a connect/disconnect command.

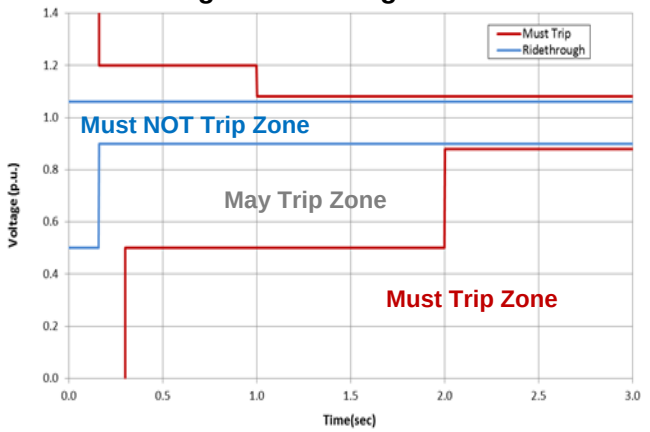
Default Deployment Settings

- CA Rule 21 Phase 1 has only autonomous functions.
  - No communication methods for updating the values.
  - Settings will remain for the lifetime of the inverter.

- WHAT SETTINGS SHOULD MANUFACTURERS USE?
- **Voltage and frequency ride-through**
  - 1547a sets stage for jurisdiction-specific requirements.
  - Will V/FRT vary with location (e.g., state-to-state)?
- **Volt-var**
  - How much deadband is necessary to maintain grid stability?
  - Some advanced function reduce inverter reliability, e.g., non-unity power factor increases IGBT switching losses

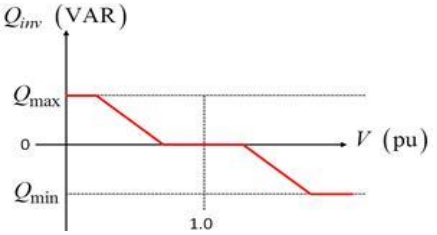
- **Modeling is critical** to determine appropriate ranges for the advanced function settings.

Voltage Ride-through Function



	Default settings		Ranges of adjustability	
Function	Frequency (Hz)	Clearing time (s)	Frequency (Hz)	Clearing time (s)
UF1	57	0.16	56 – 60	0 – 10
UF2	59.5	20	56 – 60	0 – 300
Power reduction	60.3	10	60 - 64	0 - 300
OF1	60.5	20	60 – 64	0 – 300
OF2	62	0.16	60 - 64	0 - 10

1547a FRT has large adjustment range.



UL 1741 Certification Settings

- **UL 1741 STP working groups are determining settings for the advanced inverter functions.**

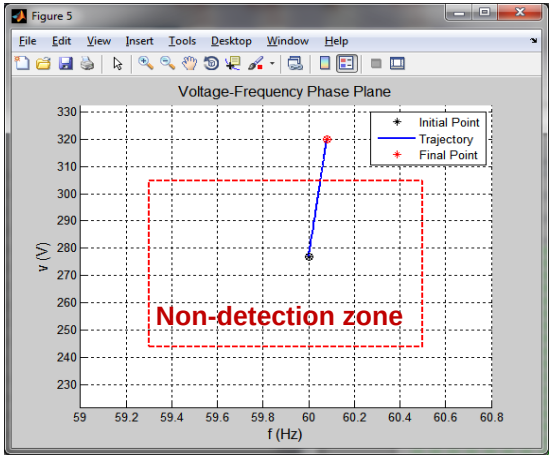
UL 1741 Advanced Grid Function Settings

Anti-islanding Tests
Advanced grid function settings → *most severe* configuration, e.g. smallest volt/var deadband, steepest volt/var and freq/watt slopes, wide-open V/FRT.

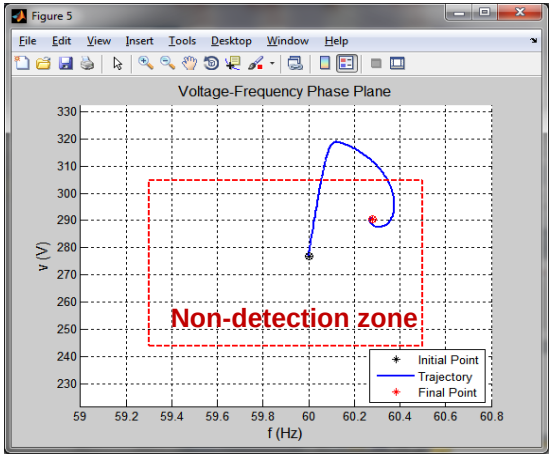
Advanced Inverter Function Tests
Minimize number of permutations → only test maximum, minimum, and default settings.

Pass/fail criteria are being developed based on manufacturers' stated accuracy

Without volt/var and freq/watt.



With volt/var and freq/watt.



Volt/var & freq/watt functions make certain anti-islanding methods less effective. Simulations of an inverter using Sandia Frequency Shift AI method shows that inverter returns to the non-detect zone with volt/var & freq/watt .

Future Work

- UL STP to develop test protocols with the UL 1741 STP for Rule 21 advanced inverter functions
  - Update anti-islanding tests and advanced function tests
- Exercise and update the UL recommendations and Sandia Test Protocols
  - Smart Grid International Research Facilities Network (SIRFN) members are testing residential inverters and comparing results.
- Create, test, and release the SunSpec Test Tool
- Create, exercise, and update energy storage systems
- Development of cybersecurity measures for the interoperability